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Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico

Abstract The impact of an improved wood burning stove (Patsari) in reducing personal exposures and indoor concentrations of particulate matter ($PM_{2.5}$) and carbon monoxide (CO) was evaluated in 60 homes in a rural community of Michoacan, Mexico. Average $PM_{2.5}$ 24-h personal exposure was 0.29 mg/m^3 and mean 48-h kitchen concentration was 1.269 mg/m^3 for participating women using the traditional open fire (fogon). If these concentrations are typical of rural conditions in Mexico, a large fraction of the population is chronically exposed to levels of pollution far higher than ambient concentrations found by the Mexican government to be harmful to human health. Installation of an improved Patsari stove in these homes resulted in 74% reduction in median 48-h $PM_{2.5}$ concentrations in kitchens and 35% reduction in median 24-h $PM_{2.5}$ personal exposures. Corresponding reductions in CO were 77% and 78% for median 48-h kitchen concentrations and median 24-h personal exposures, respectively. The relationship between reductions in median kitchen concentrations and reductions in median personal exposures not only changed for different pollutants, but also differed between traditional and improved stove type, and by stove adoption category. If these reductions are typical, significant bias in the relationship between reductions in particle concentrations and reductions in health impacts may result, if reductions in kitchen concentrations are used as a proxy for personal exposure reductions when evaluating stove interventions. In addition, personal exposure reductions for CO may not reflect similar reductions for $PM_{2.5}$. This implies that $PM_{2.5}$ personal exposure measurements should be collected or indoor measurements should be combined with better time–activity estimates, which would more accurately reflect the contributions of indoor concentrations to personal exposures.

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Key words: Exposure bias; Biomass stoves; Indoor air pollution; Particulate matter; Carbon monoxide.

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Practical Implications

Installation of improved cookstoves may result in significant reductions in indoor concentrations of carbon monoxide and fine particulate matter ($PM_{2.5}$), with concurrent but lower reductions in personal exposures. Significant errors may result if reductions in kitchen concentrations are used as a proxy for personal exposure reductions when evaluating stove interventions in epidemiological investigations. Similarly, time microenvironment activity models in these rural homes do not provide robust estimates of individual exposures due to the large spatial heterogeneity in pollutant concentrations and the lack of resolution of time activity diaries to capture movement through these microenvironments.

Introduction

Approximately half the world's population and up to 90% of rural households in developing countries still rely on solid fuels as their primary energy source (Bruce et al., 2000). Indoor solid fuel burning in open fires results in about 1.6 million premature deaths per year and represents near 4% of the global burden of disease, with a disproportionate burden falling on

women and small children (Smith, 2006). Health effects of wood smoke have been comprehensively reviewed by Naeher et al. (2005), who found consistent evidence that biomass smoke increases risks of morbidity and mortality (Albalak et al., 2001, Smith and Ezzati, 2005; Von Schirndig et al., 2002). There is strong evidence for the role of indoor air pollution from unvented stoves in acute lower respiratory infections, the single most important cause of mortality in children aged under 5 years, chronic obstructive pulmonary disease, bronchitis and lung cancer (Bruce et al., 2000). In Mexico almost 80% of the rural population, or about 25 million people, depend on wood for cooking, heating and other domestic tasks (Masera et al., 2005) resulting in significant exposures of the rural population to pollutants in wood smoke, and a significant health burden (Riojas-Rodríguez et al., 2006). There is therefore a critical need for interventions to effectively reduce exposures of these populations. While there are a number of technologies that have the potential to significantly reduce emissions of air pollutants to the indoor environment, the exposure reductions have often not been realized in practice because of barriers of cost, suitability for cooking tasks and acceptance by local populations.

Although improved stoves have been promoted in Mexico for 15 years, primarily for reduction in fuel consumption and associated deforestation (Masera et al., 2000), there has been little systematic evaluation in Mexico of the reduction in indoor concentrations that result from installation of an improved stove. Even less information is available on the corresponding reduction in personal exposures, especially in situations where continued use of traditional stoves for some cooking tasks prevail. Most epidemiological research on the effects of biomass fuel use on health relies on questionnaire information on fuel and stove type, or use indoor concentrations measured over a 24-h period, which may not accurately characterize the exposure patterns of study participants. It is therefore important to assess reductions in kitchen and personal exposure concentrations relative to different stove usage patterns, and the relationship of personal exposure reductions to those seen in kitchen concentrations. Without careful assessment of these potential sources of bias, significant error may be incorporated when attributing pollutant concentrations to health effects in these populations.

The Patsari project represents a unique effort to obtain a broad understanding of rural dynamics (Berrueta et al., 2007), personal exposure reduction (Zuk et al., 2006), health effects (Riojas-Rodríguez et al., 2006), greenhouse gas emissions (Johnson et al., 2007), social and environmental impacts and evolution of the technology dissemination (Troncoso et al., 2007) and adoption process through the installation and evaluation of Patsaris in the state of Michoacan, Mexico. This paper addresses the reductions in personal exposures of women to $PM_{2.5}$ and CO in comparison with reductions in kitchen concentrations because of the installation of a vented Patsari stove.

Methods

Stove designs

Similar to many rural areas worldwide, multiple types of stoves and combinations of fuels are used in Michoacan. The most prevalent of these stoves is the 'fogon', an open fire surrounded by a U shape of mud/brick/cement blocks, with iron bars on the top on which is placed a 'comal' (a flat pottery dish or metal hotplate for cooking tortillas or other traditional maize dishes) or pots to cook (Figure 1a). The open side of the fogon is used to add fuel to the fire, and smoke is emitted directly to the room, as there is no flue or chimney. Henceforward we refer to this stove as the fogon or 'traditional' stove to distinguish it from the 'improved' stove or Patsari.

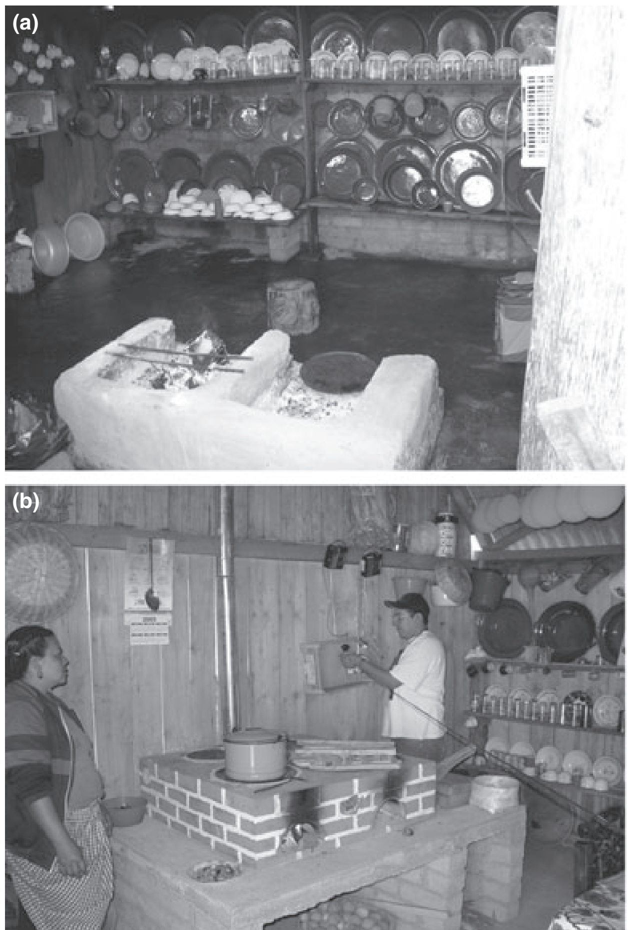

Fig. 1 Typical kitchens, showing (a) traditional Fogon and (b) improved Patsari stove

The Patsari stove was developed for rural people as an alternative to the fogon with the following objectives: (a) affordable technology to meet cooking needs accepted by local populations; (b) diminish health impacts resulting from exposure to smoke in kitchens; (c) reduce wood consumption to mitigate the difficulty and expense associated with access to fuel wood.

The Patsari stove has a closed combustion chamber surrounded by bricks which are often decorated with ceramic tiles by the homeowners. A comal is integrally built into the surface of the stove, which has a smaller entrance for feeding fuel and a flue that passes through the roof and conveys the smoke outdoors (Figure 1b) (Masera et al., 2005).

Study site and sample population

In the central Mexican highlands in the state of Michoacan, 15 municipalities were selected where reliance on biomass fuels for primary energy provision was over 80% (Masera et al., 2005). From these municipalities 600 homes were randomly selected in six Purepecha communities for participation in a community intervention trial of the effects of the improved Patsari stove on respiratory health effects where families were randomly selected into intervention and control groups. The sample selected for estimation of reductions in personal exposures and indoor air pollution levels presented in this study was selected from the intervention group in Comachuen, an indigenous agricultural community of 4300 habitants located 2600 m above sea level, where the majority of families (98%) rely on traditional fogons and wood for cooking.

Study participants consisted of residents of 60 homes randomly selected from intervention homes where the kitchen was enclosed by four walls and were not shared between families; families contained between five and nine members; and participating women stated a desire to use the Patsari stove. The objectives were not to represent all possible family sizes and kitchen and stove arrangements in the community, which would have required a much larger sample size and cost, but rather to represent the enclosed kitchens that are common in the region. Figure 2 shows the typical distribution of rooms in a rural house in Comachuen. Protocols for inclusion of human subjects and informed consent procedures were approved by Institutional Review Board committee at the University of California at Irvine and from participating institutes in Mexico.

Fig. 2 Typical layout of home in Comachuen

Instrumentation

Particulate matter was measured using the University of California at Berkeley Particle Monitor (Berkeley, CA, USA) (henceforward referred to as UCB), a semi-continuous (1-min averages), light-scattering nephelometer (Edwards et al., 2006a,b). While the UCB does not select a traditional cutoff point, the photoelectric sensor is most sensitive to particles less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) (Litton et al., 2004). Laboratory validation of UCB particle monitor response in relation to particle size for monodisperse aerosols and combustion particles has been characterized by Edwards et al. (2006a,b). Field validation of the use of the UCB particle monitor to estimate $PM_{2.5}$ concentrations in biomass-burning kitchens has been presented by Chowdhury et al. (2007) including quality assurance measures collected during the course of the current study in Mexico.

To ensure comparability of the real-time $PM_{2.5}$ concentration estimates of the UCB, three quality assurance measures were undertaken: (1) as multiple instruments were deployed in different microenvironments, inter-instrument variability in aerosol sensitivity was adjusted over the course of the study in a series of four controlled co-locations within a cylindrical 1.2-m diameter steel combustion chamber using combustion aerosols generated by controlled combustion of small pieces of fuel wood collected from study homes. The methodology for the chamber testing is presented in detail in Chowdhury et al. (2007). Correlation between mean UCB mass and $PM_{2.5}$ gravimetric samples during the co-location chamber tests yielded R^2 values 0.98 or better, the slopes of which were used to normalize inter-instrument variability in response against gravimetric samples. (2) As nephelometer sensitivity is a function of an aerosol's specific optical properties such as size, color, and shape, calibration of UCB response with the target aerosol is required. Correlation between the normalized UCB photoelectric response and co-located 48-h $PM_{2.5}$ gravimetric measurements in 41 kitchens showed good agreement (n = 41, R^2 = 0.90), and was used to estimate $PM_{2.5}$ concentrations (Figure 3). (3) Duplicate samples in which two UCBs were co-located next to each other in the field home were collected in 28 homes (Figure 4). The average

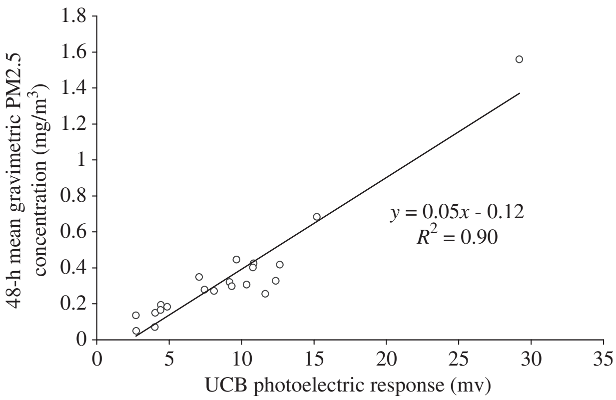

Fig. 3 Mass calibration of UCB against collocated $PM_{2.5}$ gravimetric samples

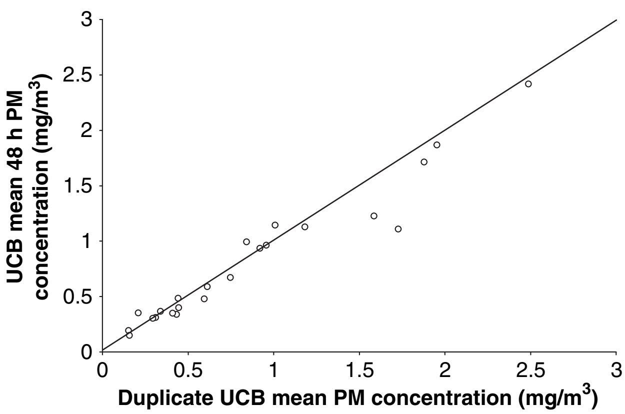

Fig. 4 Duplicate UCB 48-h mean measurements

percentage difference in 48-h average mass estimates between UCB duplicates was 14%, with good agreement between different UCB monitors (standard error 0.066; Pearson's $r^2 = 0.94$; $P < 0.001$).

Gravimetric $PM_{2.5}$ samples were collected using standard air sampling pumps (Model 224-PCXR8; SKC Inc., Eighty Four, PA, USA) with $PM_{2.5}$ cyclones (BGI Triplex Cyclone-BGI, Waltham, MA, USA) using a flow rate of 1.5 l/min. Flow rates were measured before and after installation of the sampling equipment in the home with a rotameter (Matheson Trigas, Montgomeryville, PA, USA), that had been calibrated using an SKC Ultra Flow bubblemeter (SKC Inc.). $PM_{2.5}$ particulate matter was collected on 37-mm, 2.0-μm-pore size Teflon filters (SKC Inc.). Filters were equilibrated for 48 h at 21 ± 2°C and 40 ± 5% relative humidity before being weighed on an electronic microbalance (Cahn Microbrobalance Model 29; Thermo Electron Corp., Waltham, MA, USA). Calibration of the microbalance response was checked with National Institute of Standards and Technology (NIST) certified calibration standards. Laboratory blank measurements were weighed before and after weighing of samples, and were within 5% of the average for all the periods. Field blank ($n = 7$) subtraction resulted in a 6.5% adjustment of the average increase in mass of the filters from the homes.

Carbon monoxide was measured using semi-continuous electrochemical CO sensors (HOBO®; Onset Corporation Inc., Bourne, MA, USA). Prior to sampling HOBO CO monitor response was compared with certified NIST traceable gas calibration standards at concentrations of 5, 10, 25 and 60 ppm (Scott Specialty Gases, Plumsteadville, PA, USA). HOBO CO monitors demonstrated good linearity against calibration standards (Pearson's $r^2 > 0.99$; $P < 0.001$). The slope of the response was different for each monitor, however, and was subsequently used to normalize inter-instrument variability in response relative to CO concentrations in gas calibration standards. Inter-instrument response was monitored in four controlled combustion chamber co-location tests to adjust for any changes over time during the monitoring period (collocated with UCB particle monitors).

Sampling design

$PM_{2.5}$ and CO concentrations were assessed during the dry season before installation of the improved Patsari stove and after 1 month of use.

Personal exposures. Semi-continuous $PM_{2.5}$ and CO personal exposures were assessed at 1-min intervals for a 24-h period; 24-h personal measurements were obtained by placing a UCB particle monitor and CO monitor in a small, locally purchased shoulder bag, which had been altered to allow airflow through a mesh surface. Because of the increased inconvenience of wearing personal exposure equipment, personal exposures were assessed for 24 h.

Microenvironment concentrations. Semi-continuous $PM_{2.5}$ and CO concentrations were recorded every minute for 48 h close to the stove, in the center of the kitchen, just outside the kitchen in the yard and in the main bedroom. Monitors close to the stove were placed at a standardized height of 1.25 m above ground, 1 m distant horizontally from the central combustion zone, and at least 1.5 m from windows and doors. Kitchen monitors were placed at least 2.5 m away from the stove and 1.5 m above the ground. The yard microenvironment was measured by placing UCB monitors 1.5 m above ground and as close as possible to where the family reported to spending the most time when outdoors. For 25% of homes stove microenvironments were monitored for 5 days to assess variability of 48-h measurements in relation to 5-day concentrations. In addition to semi-continuous measures, 48-h $PM_{2.5}$ gravimetric measurements were collected in kitchens for a subset of homes ($n = 41$), and ambient concentrations were measured throughout the study period on

the roof of the local health clinic at the center of the community.

Structured interviews were conducted at the end of each 24-h period with a household questionnaire and time–activity log. Household questionnaires collected information on home and kitchen characteristics, stove use, fuel type, and other potential air pollution sources. For time–activity information participants were asked to remember and enumerate each cooking activity, duration, type of stove and fuel used and time spent in the kitchen during the day.

Statistical analysis

All data were analyzed with STATISTICA (Version 2001; StatSoft, Inc., Tulsa, OK, USA). Non-parametric Wilcoxon signed rank tests (SRT) were used to compare personal exposure and indoor concentrations before and after installation of the improved Patsari stove. Outliers and extreme values for boxplots were defined as values larger or smaller than four or seven times the standard error from the median respectively.

Results

Study participation

Although 60 homes were selected to characterize the reductions in mothers' personal exposures and kitchen concentrations in relation to stove usage patterns in homes that adopted the improved stove, it was anticipated that a number of these homes would not complete the study for a variety of reasons, including deciding not to install the improved stove. As drop out from the study may be unrelated to stove adoption, which is required to assess the overall impact of the improved stove intervention, the reasons for non-participation were assessed for each group and are presented in Table 1. A total of 26 homes were not monitored after the installation of the improved Patsari stove, of which four were no longer willing to participate because of the requirements of the health study, three were no longer willing to participate in the indoor air monitoring and two were unable to be located at the time of the post-installation monitoring. Of the remaining 17 homes, monitoring was not conducted in eight because either a new kitchen was built to house the patsari or because the participants changed homes. Monitoring was also not conducted in a home that had modified the Patsari by removing the comal. The remaining eight homes had problems adapting to the requirements of the stove and had not adopted the Patsari.

Table 1 Participation rates for baseline and post-monitoring campaigns

Baseline measurements of traditional fogon	60
Monitored post-Patsari installation	34
Not monitored post-installation	26
Withdrew participation	
Health	4
Indoor air monitoring	3
Unable to be located	2
Not monitored	
Were building new kitchen	4
Plans to move to another house	2
Husband migrated – moved in with relative	2
Requested additional training	4
Problems with stove requirements	4
Modified improved stove	1

Reductions in personal exposures

Particulate matter. Average 24-h personal exposures to $PM_{2.5}$ for women using the traditional fogon were 0.29 mg/m^3 for all 60 participating women. Table 2 and Figure 5 show personal exposures to $PM_{2.5}$ for homes that adopted the Patsari stove both on an aggregate level and stratified by stove usage patterns, where participants retained a traditional fogon in the same room, another room, or the yard mainly for heating bath water and cooking of nixtamal.[1] On an aggregate basis for those with paired before and after measures median 24-h personal exposures were 0.17 mg/m^3 for women with a traditional fogon and 0.11 mg/m^3 with an improved Patsari. This represents a 35% reduction ($P < 0.0001$) in median personal exposures to $PM_{2.5}$ notwithstanding differences in stove adoption patterns (Table 2). For individuals who adopted the improved Patsari stove exclusively, median reductions were greater at 38% ($P < 0.04$; Table 2). As would be expected little reduction in the median $PM_{2.5}$ personal exposure concentrations was seen when another traditional stove was present in the same room (2%, $n = 11$). When the traditional stove was in the yard, or another room, a median reduction in personal exposure was still observed although less than that of exclusive Patsari users (27%, $n = 9$). The lack of statistically significance for comparisons when a traditional stove was retained also reflects the low sample numbers when stratified by store user group. In addition to reductions in the median concentrations, the variability in $PM_{2.5}$ personal exposures was reduced for exclusive Patsari users, and those who had a traditional stove outside or in the yard, when compared with the traditional stove and those participants who had a Patsari and traditional stove in the same room. Maximum 24-h average exposures for exclusive Patsari users and those with a Fogon outside or in another room were also similarly reduced, while the maximum with a traditional stove in the same room remained at levels similar to those seen before installation of the improved stove.

[1]Nixtamal is a corn base cooked once a week and subsequently used daily for cooking tortillas, the traditional Mexican accompaniment for daily meals.

Table 2 Reductions in $PM_{2.5}$ 24-h personal exposures and 48-h kitchen concentrations after installation of the Patsari improved stove

PM: (mg/m^3)	N	Before				After				Wilcoxon SRT	% Change
		Average	Median	s.d.	Maximum	Average	Median	s.d.	Maximum	*P*-value	Median
Personal exposure											
All participants	26	0.24	0.17	0.23	0.80	0.16	0.11	0.13	0.63	<0.001	35
Patsari only	6	0.18	0.15	0.09	0.36	0.09	0.09	0.02	0.11	<0.04	38
Patsari with fogon inside kitchen	11	0.25	0.20	0.18	0.62	0.22	0.19	0.17	0.63	NS	2
Patsari with fogon outside	9	0.26	0.15	0.23	0.80	0.14	0.11	0.08	0.33	NS	27
Kitchen concentration											
All participants	33	1.02	0.91	0.79	4.23	0.35	0.24	0.27	1.16	<0.001	74
Patsari only	7	1.04	1.00	0.76	2.53	0.32	0.21	0.37	1.16	<0.02	79
Patsari with fogon inside kitchen	14	1.25	1.01	1.05	4.23	0.38	0.30	0.24	0.94	<0.01	70
Patsari with fogon outside	12	0.75	0.73	0.23	1.03	0.32	0.23	0.23	0.74	<0.01	68

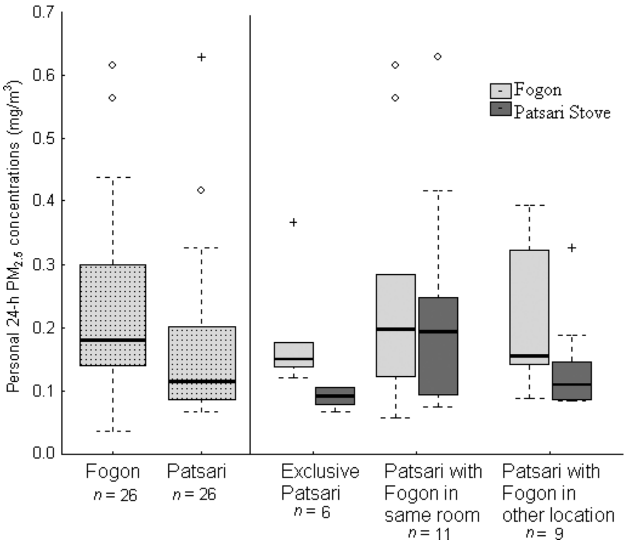

Fig. 5 UCB $PM_{2.5}$ 24-h personal exposure reductions before and after installation of the Patsari improved stove and stratified by stove usage patterns

Carbon monoxide. Average 24-h CO personal exposures for women using the traditional fogon were 2.35 ppm ($n = 60$). Table 3 and Figure 6 show CO personal exposure reductions for homes that adopted the Patsari stove both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures ($n = 24$), median personal exposures with the traditional stove were 2.3 ppm for women with a traditional fogon and 0.5 ppm with an improved Patsari, respectively. This represents a 78% reduction in median personal exposures notwithstanding differences in stove adoption patterns (Table 3). For individuals who adopted the improved Patsari stove exclusively the reduction in median personal exposures was 54% (Table 3). For those with a traditional stove retained in the kitchen reductions were 78% and for those with a traditional stove in another room or in the yard the reductions were 86%. Similar to the pattern of $PM_{2.5}$ exposures, maximum 24-h average exposures for those who retained a traditional stove in the same room remained similar to levels seen before installation of the improved stove. For improved stoves where a traditional stove in the same room was not present, maximum 24-h exposures were considerably reduced compared with traditional stoves. Similar patterns were seen in reduction of variability in 24-h average personal exposures.

Reductions in kitchen concentrations

Particulate matter. Mean 48-h $PM_{2.5}$ kitchen concentration in homes with the traditional fogon was 1.27 mg/m^3 ($n = 60$). Table 2 and Figure 7 show $PM_{2.5}$ kitchen concentrations for homes where the

Table 3 Reductions in CO 24-h personal exposures and 48-h kitchen concentrations after installation of the Patsari improved stove

CO: (ppm)	*n*	Before				After				Wilcoxon SRT	% Change
		Average	Median	s.d.	Maximum	Average	Median	s.d.	Maximum	*P*-value	Median
Personal exposures											
All participants	24	2.7	2.3	2.1	8.3	1.0	0.5	1.6	8.3	<0.0001	78
Patsari only	5	1.3	1.3	0.7	2.4	0.7	0.6	0.4	1.4	NS	54
Patsari with Fogon inside kitchen	11	2.7	2.3	2.0	7.4	1.6	0.5	2.5	8.3	<0.07	78
Patsari with Fogon outside	8	3.6	3.6	2.4	8.3	0.6	0.5	0.3	1.0	NS	86
Kitchen concentrations											
All participants	32	8.9	8.6	4.4	22.6	3.0	2.0	2.7	12.1	0.05	77
Patsari only	7	7.8	7.3	3.9	16.3	1.6	1.2	1.1	3.7	<0.04	83
Patsari with Fogon inside kitchen	13	10.8	10.4	5.2	22.6	3.5	3.3	2.7	12.1	<0.01	68
Patsari with Fogon outside	12	7.4	8.4	3.1	11.3	3.1	2.0	3.1	9.5	<0.07	76

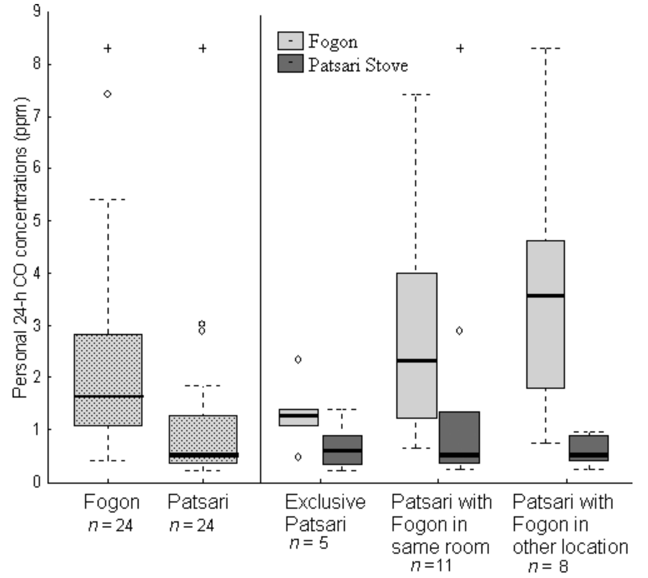

Fig. 6 24-hour CO personal exposure reductions before and after installation of the Patsari improved stove and stratified by stove usage patterns

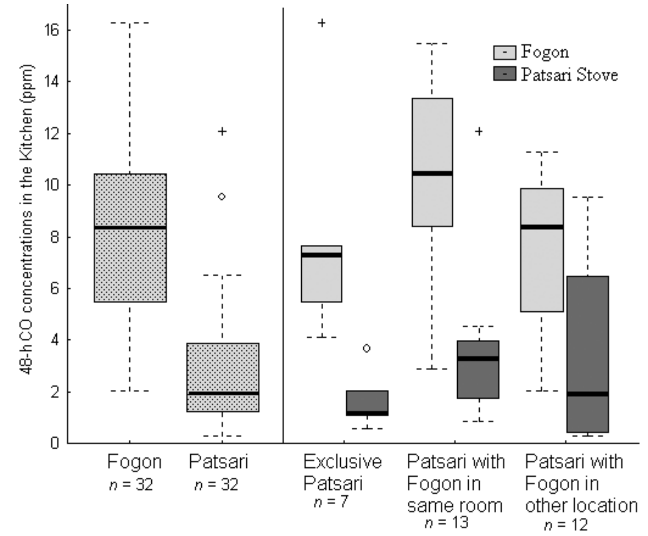

Fig. 8 48-hour CO concentrations in kitchens before and after installation of the Patsari improved stove and stratified by stove usage patterns

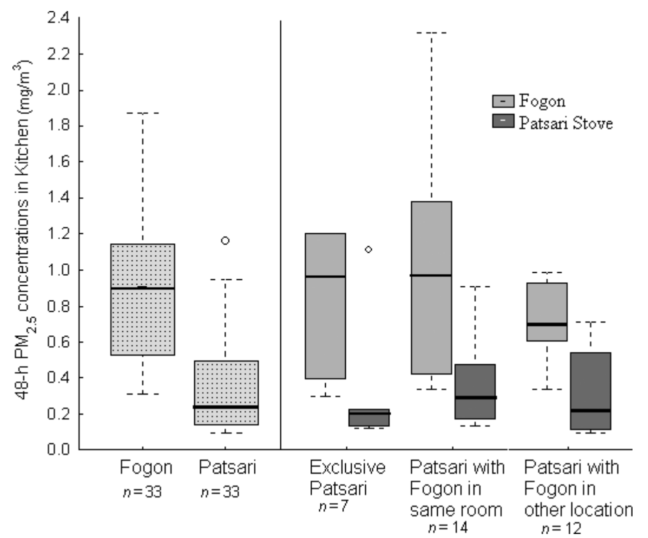

Fig. 7 48-hour $PM_{2.5}$ concentrations in kitchens before and after installation of the Patsari improved stove and stratified by stove usage patterns

Patsari stove was adopted both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures ($n = 33$), median 48-h kitchen concentrations were 0.91 mg/m^3 with a traditional fogon and 0.24 mg/m^3 with an improved Patsari. This represents a 74% reduction in median 48-h kitchen concentrations notwithstanding differences in stove adoption patterns. For homes that used the Patsari stove exclusively, the reduction in median 48-h CO kitchen concentrations was 79%. For homes where a traditional stove continued to be used in the kitchen, the reduction in median concentrations was 70% and when a traditional stove continued to be used outside or in another room, the reduction in median concentrations was 68%.

Carbon monoxide. Mean 48-h kitchen CO concentration in homes with the traditional fogon was 8.2 ppm ($n = 60$). Table 3 and Figure 8 show kitchen concentrations for homes where the Patsari stove was adopted both on an aggregate level and stratified by stove usage patterns. On an aggregate basis for those with paired before and after measures ($n = 32$), the median 48-h kitchen concentration for women with a traditional fogon was 8.6 and 2.0 ppm after installation of an improved Patsari, respectively. This represents a 77% reduction in kitchen concentrations notwithstanding differences in stove usage patterns. For individuals who adopted the improved Patsari stove exclusively the reduction in median kitchen concentrations was 83%. For those with a traditional stove still in the same room the reductions were reduced to 68%, and for those kitchens with a fogon in another location reductions were somewhat greater (76%) in comparison.

48-h averages vs. 5-day averages

$PM_{2.5}$ kitchen concentrations were monitored (using semi-continuous UCB monitors) for approximately 5 days in a sub-sample of 24 of the 60 homes with a traditional fogon and 10 of the 34 homes after installation of the Patsari to estimate the extent that 48-h sampling times in the rest of the homes represented the longer sampling period. As sampling times were slightly short of the complete 5 days of sampling we restrict our analyses to four complete 24-h periods to better assess variability. Figure 9 shows the reduc-

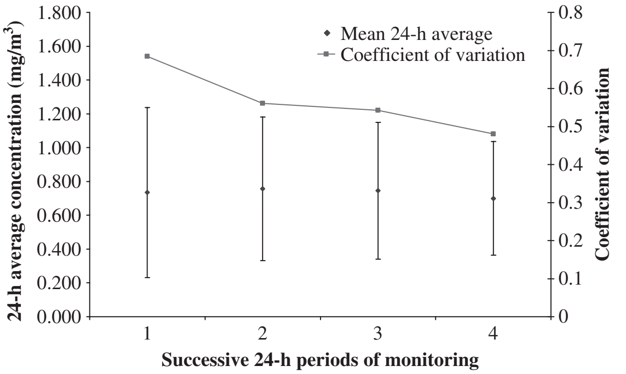

Fig. 9 Reduction in coefficient of variation (COV) associated with successive 24-h periods of monitoring for 24 homes with traditional fogons

Note: Error bars represent the standard deviation of 24-h average $PM_{2.5}$ concentrations for homes with traditional fogons, which is reduced with inclusion of each successive 24-hour period into the monitoring average.

tion in variability of average $PM_{2.5}$ estimates in homes using a traditional fogon as successive 24-h periods are included. The coefficient of variation (COV) of the mean $PM_{2.5}$ concentrations for the 24 homes reduced from 0.68 for one 24-h period to 0.48 for the 4-day period; 60% of this reduction occurred in the first 48 h. Similarly, for homes using the Patsari stove with four complete 24-h periods of $PM_{2.5}$ monitoring, the COV reduced from 0.70 to 0.55, with 54% of the reduction occurring during the first 48 h.

Discussion

Although there have been improved stove dissemination projects in Mexico since the 1980s there has been little formal in-field evaluation of the effectiveness of the intervention in reducing exposure to indoor air pollution. While efficacy measurements that test indoor air reductions in controlled settings give an idea of the maximum achievable benefit, it is critical that in-field evaluations are also performed to assess actual impacts for different stove usage groups in communities where the stove is adopted. Such assessments, of course, are much more difficult and complex to make, aside from logistical issues often involving remote rural communities, and relying on goodwill of communities for participation. As stated by Rogers (1995), different rates of adoption of the improved stove would be expected both within rural communities based on different adopter categories, and between communities based on affluence and exposure to other new technologies. In the case of improved stoves, however, the picture is more complex, because both the pace and degree of adoption need to be considered. As noted by Masera et al. (2000) rather than simply replacing one cooking technology by another, households often rely on multiple combinations of fuels and technologies to meet their cooking needs creating different stove usage groups. Although anecdotal, adoption rates of the improved stove in the current study would tend to support social theories of technology dissemination in that there were participants who adapted to exclusive use of the new technology, participants that partially adopted it but retained the traditional stove either in the same room or elsewhere around the house, participants who required further instructions in the use and maintenance of the stove, and participants who appeared to reject the new technology. Identifying the characteristics of these groups is critical in achieving the maximum benefit from the stove dissemination effort, as the effectiveness of an improved stove dissemination program lies in the numbers adopted, used and maintained, rather than simply the number of stoves disseminated. Not only is this important to maximize the effect of limited funds and manpower for stove dissemination, it is also important in the dissemination process as communication within the community on the performance of the technology is an important aspect in persuading the more cautious adopter groups of the benefits of the new technology.

Reductions in personal exposures and kitchen concentrations

As in many rural communities worldwide, there are a wide variety of stoves, fuels, kitchen constructions and layouts combined with a wide range of family sizes that are prevalent in this region of Mexico, which is hard to capture in a statistically representative manner, without resource prohibitive sample sizes. As monitoring was only conducted in one community for logistical reasons, reductions in $PM_{2.5}$ and CO exposures and kitchen concentrations do not necessarily represent different communities in Michoacan or all possible arrangements in these communities, but rather are indicative of what one might expect with the Patsari stove in similar biomass using communities.

On an aggregate basis, paired comparisons indicated a 35% reduction in median 24-h $PM_{2.5}$ exposure and a 78% reduction in median 24-h CO exposures respectively (Wilcoxon SRT, $n = 26$ $P < 0.001$ and $n = 24$ $P < 0.0001$, respectively). Similarly, paired comparisons of 48-h median kitchen concentrations indicated a 74% reduction in median particulate mass concentrations, and a 77% reduction in median CO concentrations (Wilcoxon SRT, $n = 33$ $P < 0.001$ and $n = 32$ $P < 0.05$, respectively). When stratified by stove usage groups reductions in median 48-hour $PM_{2.5}$ kitchen concentration were 79%, 70% and 68% for homes with exclusive Patsari use, homes using a Patsari and a fogon in the same room, and homes using a Patsari with a fogon in another location, respectively. Similar reductions were observed for median carbon monoxide 48-h kitchen concentrations with 83% and 68% for

Table 4 Ratio of average and median $PM_{2.5}$ and CO personal exposures to kitchen concentrations

	Average			Median		
	Before	After	Difference	Before	After	Difference
Particulate mass (%)						
All stove adoption groups	24	46	−22	18	46	−28
Exclusive Patsari users	17	28	−11	15	44	−30
Patsari with traditional fogon in kitchen	20	58	−38	19	63	−44
Patsari with traditional fogon in other location	35	44	−9	21	48	−27
Carbon monoxide (%)						
All stove adoption groups	31	33	−3	27	26	2
Exclusive Patsari users	17	43	−26	17	46	−29
Patsari with traditional in kitchen fogon	25	45	−20	22	15	7
Patsari with traditional fogon in other location	49	19	29	43	26	17

exclusive Patsari users and Patsari users with a fogon inside the kitchen, respectively, and 76% for Patsari users with a fogon in another location.

Percentage reductions in personal exposures were consistently smaller for particulates than they were for CO. While the ratio of CO and particulate matter emissions vary depending on the stage of combustion (smoldering vs. flaming for example) as they are not formed by the same chemical processes in combustion, this is unlikely to be the cause of the different reductions in personal exposure as the kitchen concentrations of both pollutants were reduced by similar percentages. Rather, the difference is likely the result of stratification of smoke in the kitchen as the fraction of personal exposures as a percentage of kitchen concentrations were also greater for CO than for $PM_{2.5}$ during the baseline when homes had traditional stoves (Table 4). As CO is a gas and more mobile it would not be similarly affected.

Although median 48-h $PM_{2.5}$ kitchen concentrations after installation of the improved Patsari stove were somewhat similar for those who were exclusive Patsari users (0.21 mg/m^3) and those who used a Fogon in a different location (0.23 mg/m^3), the decreased percentage reductions in kitchen concentrations for the latter group (68% vs. 79%) were driven by lower initial fogon concentrations. Given that family sizes were similar, the lower initial fogon concentrations suggests either some fundamental difference between households and cooking habits, or that these homes may have already been using a fogon in another location for some cooking tasks. Although percentage reductions of $PM_{2.5}$ concentrations in kitchens that retained a traditional fogon in the same room were high, as expected the resultant median 48-h concentrations (0.30 mg/m^3) were higher than in kitchens of exclusive Patsari users (0.21 mg/m^3) and those who used a fogon in another location (0.23 mg/m^3). Percentage reductions in kitchen concentrations were high for those with a traditional stove in the same kitchen because of relatively infrequent use of the traditional fogon for cooking of nixtamal or water for bathing, although similar reductions in personal exposures were not observed which may indicate a change in behavior.

In addition to reducing central tendency measures of $PM_{2.5}$ kitchen and personal exposure concentrations, installation of the Patsari stove also reduced maximum $PM_{2.5}$ kitchen and personal exposure concentrations in this sample population except for maximum personal exposure when the fogon remained in use in the same room as the Patsari. Similarly, installation of the improved Patsari stove also resulted in decreased maximum CO kitchen and personal exposure concentrations, again with the exception of maximum personal exposure when the fogon remained in use in the same room as the Patsari. Although peak exposures and kitchens concentrations measured in each home were also reduced after installation of the Patsari, more detailed health effect studies would have to be performed to evaluate the health implications of reduction in these peak concentrations.

Prior studies in rural Mexico have demonstrated that typical mean $PM_{2.5}$ kitchen concentrations of 0.887 mg/m^3 with maximum concentrations around 2.0 mg/m^3 for cooking periods depending on type of fuel, stove and ventilation (Brauer, 1998). Mean 48-hour kitchen concentrations for fogons in the current study (0.950 mg/m^3) fall in this range and in the range of comparable studies worldwide (Naeher et al., 2000; range: 0.26–13.80 mg/m^3), but are somewhat lower than those seen in India (Balakrishnan et al., 2002; range: 0.5–2 mg/m^3). After installation of the improved stove the median 24-h kitchen concentrations of $PM_{2.5}$ was still approximately 4 times higher (0.24 mg/m^3) than Mexican Ambient Standards of 0.065 mg/m^3 (SSA, 2005) and 4.5 times the WHO interim standard of 0.075 mg/m^3 as a 24-h mean. Although average 48 hour yard concentrations (0.094 mg/m^3) also exceeded the WHO interim standard, they were not out of the range of what was achievable in reductions given that ambient concentrations at the local health center were below the interim standard (0.059 mg/m^3). For CO previous studies have reported concentrations between 10–500 ppm in kitchens during stove use and 2–50 ppm over 24 h (Von Schirndig et al., 2002). The maximum 48-h CO concentrations were of similar magnitude in homes using the traditional fogon in the current study and 48-h averages ranged from 2 to 22 ppm, with means exceeding 50 ppm during periods when the stove was lit.

As reported by Zuk et al. (2006), patio and ambient $PM_{2.5}$ concentrations were 0.094 and 0.059 mg/m^3 and no significant differences after installation of the improved stove were detected. Patio concentrations appear to show an elevated neighborhood effect from

the fugitive emissions of stoves from surrounding homes and from their own (Smith et al., 1994), as 99% of participants reported no burning of trash in the area surrounding their home as additional sources and vehicle traffic in this community is very low. As outdoor sources were similar between the baseline period and post Patsari installation the reductions in particulate and CO concentrations in kitchens do not suffer from bias as a result of large differences in environmental conditions between measurement periods.

None of the women participants in this community consumed tobacco, which is typical of rural communities in this area of Mexico. While some environmental tobacco smoke (ETS) exposure may be present as a result of husbands smoking, the contribution of $PM_{2.5}$ and CO to indoor concentrations from ETS would be extremely small compared to the contribution of the stove for women in these homes. In an evaluation of 400 solid fuel using homes in China as part of a review of the National Improved Stove Program, the effects of smoking on indoor concentrations in the presence of solid fuel burning stoves were not discernable (Edwards et al., 2006a,b). As indoor concentrations in livingrooms were also assessed in the current study and no additional sources of particulates and CO were observed, comparisons of kitchen concentrations and personal exposures were not biased by other large sources of exposure.

In spite of efforts to constrain the variability between homes via household selection criteria, the variability in all groups remained high (Figure 9), where between home variability was approximately double the within home variability for those homes measured over 5 days. Although this variability may be the result of different ventilation status of the homes, which was a significant predictor of indoor levels in India (Smith et al., 2004), we tested only one type of kitchen arrangement, and the semi-continuous records of particulate and CO concentrations suggested that different stove usage patterns may dominate the variability. Questionnaires should therefore focus their efforts exploring this aspect of stove usage.

Relationships of personal exposures to kitchen concentrations

Table 4 shows the ratio of personal exposures to kitchen concentrations before and after installation of the improved stove. As there was an additional stove in another room in the house, or in the yard, that was used for some cooking activities frequently at the same time as the main stove, relationships between kitchen reductions and personal exposure reductions can not be directly derived, although it highlights the the limitations of using indoor concentrations as an estimate of personal exposures. Similar usage of additional stoves and fuels were also observed in China in a review of the National Improved Stove Program (Edwards et al., 2006a,b).

For participants who exclusively adopted a Patsari stove average $PM_{2.5}$ personal exposures were equivalent to 17% of kitchen concentrations for the traditional fogon and 28% after installation of the Patsari in paired comparisons. For participants who maintained a traditional fogon in the same room as the Patsari, however, $PM_{2.5}$ personal exposures were equivalent to 20% of kitchen concentrations for the traditional fogon and 58% after installation of the Patsari in paired comparisons. Thus, the relationship between personal exposures and indoor concentrations not only changed between traditional and improved stove type, but also differed by stove adoption category. Using kitchen concentrations to estimate reductions in personal exposures as a result of installation of an improved stove would therefore result in a bias of 11% and 38% for exclusive patsari users, and those that retained a fogon in the same room, respectively.

Carbon monoxide exposures showed a similar pattern. For those who were exclusive users of a Patsari stove average CO personal exposures were equivalent to 17% of kitchen concentrations for the traditional fogon, and 43% after installation of the improved Patsari. For those who retained a traditional fogon in the kitchen average personal exposures were equivalent to 25% of kitchen concentrations with the traditional fogon, and 45% after installation of the improved Patsari. Thus, for CO using kitchen concentrations to estimate reductions in personal exposures as a result of installation of an improved stove would result in a potential bias of 20% and 26% for exclusive patsari users, and those that retained a fogon in the same room, respectively.

The increase in the ratio of personal exposures to kitchen concentrations after installation of the improved stove may be the result of several factors: (1) the improved Patsari stove may take longer to cook specific food items requiring increased time spent near the stove. There is some evidence of this from stove performance tests (Berrueta et al., 2007), however, more detailed evaluation of this aspect would have to be undertaken using direct observation or other methods such as personal locator transmitters (Allen-Piccolo, unpublished data). Recall time–activity diaries in these settings lack the resolution to adequately quantify the differences in time spent in front of the stove. (2) As $PM_{2.5}$ and CO concentrations in indoor environments were reduced, more time may be spent in the kitchen for other reasons. For example, in these 60 homes 93% of families reported eating in the same kitchen where the food was prepared. Although anecdotal some women reported increased use of the kitchen after Patsari installation for children to do homework and play and for themselves to do embroidery.

Although many other studies undertaken around the world, mostly for research purposes, have used indoor measurements to assess the health implications of solid fuel using stoves, few have collected personal exposure samples to assess potential bias in using indoor concentrations as an estimate of personal exposures. Although it has been reported in the US and Europe (e.g. Koistinen et al., 2004; Jantunen et al., 2003), estimating this bias is even more important in rural solid fuel-using households because of strong localized sources and huge spatial and temporal variability in concentrations. Thus, while indoor concentrations under-represent exposures in Finland, in rural Mexican homes kitchen concentrations far exceed personal exposures, and relatively small differences in the time spent in the kitchen may lead to significant differences in personal exposures. Perhaps more importantly, as the ratio of personal exposures to kitchen concentrations varies depending on stove usage group, significant bias can be introduced when associating reductions in $PM_{2.5}$ kitchen concentrations as a proxy for personal exposures with reduced health impacts. This aspect has been little explored in these settings, and is not evaluated as part of most epidemiologic investigations.

A frequently used approach in the US and Europe is to use microenvironment concentrations to reconstruct personal exposures based on time–activity–microenvironment models (Schwab et al., 1990). While this has been used extensively to estimate population-based exposures in the US (McCurdy and Graham, 2003), there are significant drawbacks to these approaches in rural communities in Michoacan, Mexico. In part this is because of the inability of time–activity recall diaries to have sufficient resolution to capture walking in and out of the kitchen, which represents differences in concentration frequently over an order of magnitude over short time periods. It is also due to the large temporal differences in kitchen concentration between when the stoves are lit, which is generally when most time is spent in the kitchen in these rural communities, and when they are not. When this high temporal variability in concentrations is averaged over 24–48 h, which time–activity–microenvironment models weight with the time spent in each microenvironment, the association of time spent in the kitchens when pollution concentrations are highest, and considerably exceed 24–48-h integrated averages, is not captured.

Figure 10 shows the correlation between time–microenvironment–activity model estimates of personal exposure (Zuk et al., 2006) and measured personal exposures for participants with both estimates, demonstrating how these metrics are not correlated. Perhaps more interesting is the systematic bias in estimation of personal exposures for participants with the traditional fogon compared to those with the improved Patsari stove. Estimates of personal exposure calculated by time–activity–microenvironment models overestimate measured exposures for participants with the traditional fogon and underestimate exposures with the improved Patsari stove. As there are no other major sources of exposure in these homes, this demonstrates that kitchen concentrations contribute differently to personal exposures before and after installation of the improved stove, which is not captured by the time–microenvironment–activity models. Thus time–microenvironment–activity models should not be used in these rural biomass using households to assess the magnitude of exposures relative to indoor concentrations or exposures or to assess individual exposures in relation to health effects, unless combined with better time–activity estimates such as those proposed using electronic locator transmitters (Allen-Piccolo et al., 2006), which would more accurately capture the contributions of the stove to personal exposures.

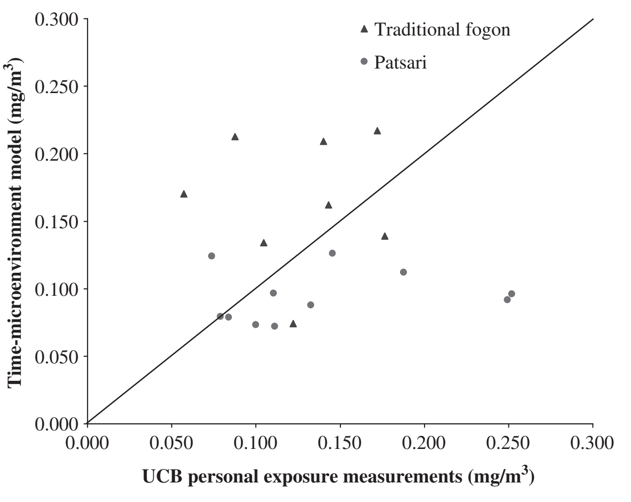

Fig. 10 Relationship between personal exposure measures and time-microenvironment models

Between- and within-home variability associated with length of sampling period

Most epidemiological investigations into the effects of biomass fuel use on exposure estimates rely on grab samples over short periods (usually 24 h). A continuing issue in collecting air pollution samples is what the optimal sampling time would be for collection of samples that minimizes impact on participants (and expense and effort required for monitoring), while achieving maximum benefit in reduction of variability between and within homes. This is not only important for sample size calculations in reducing the number of homes that are needed to show statistically significant differences, it is also important in reducing potential bias in median or mean values used to estimate the effectiveness of the improved stove.

Average within-home variability for the four complete 24-h periods in homes with a traditional fogon ($n = 24$), was 50% of between-home variability (0.22 and 0.44 mg/m^3, respectively). Similarly for homes using the Patsari stove ($n = 10$) the within-home variability was 56% of between-home variability (0.14 and 0.25 mg/m^3, respectively). Thus, in spite of efforts to restrict between-home variability through selecting the housing type, family size, stove location, the overall variability remained high because of individual stove usage patterns, although lower than typical values reported in the literature.

Figure 9 shows reductions in variability associated with monitoring for successive 24-h periods in kitchen environments with the traditional fogon; 60% of the total reduction in the coefficient of variation achieved in kitchen concentrations was achieved after 48 h. Similarly, for $PM_{2.5}$ measurements made in kitchens using the Patsari stove 54% of the total reduction in the coefficient of variation was achieved after 48 h. Although selection of a 48-h sampling period reduced the coefficient of variation by 18% for homes with the traditional fogon and 12% for homes with the improved Patsari stove, the overall variability remained high. While two more days of sampling would have achieved an additional 12% reduction in the coefficient of variation for the traditional fogon and 10% reduction for the Patsari, adding five homes to initial sample resulted in approximately 5–9% decrease in coefficient of variation. Thus, greater benefit would be more likely from an increase in the number of homes sampled rather than increasing the sampling duration given limited time and resources.

Interestingly, extending the sampling period in successive 24-h periods up to 4 days did not substantially change the average estimates of particle concentrations in kitchens in traditional fogon or Patsari homes. A difference of 0.057 mg/m^3 in 48-h average concentrations compared to 4-day average concentrations was observed for homes with traditional fogons compared to 0.011 mg/m^3 for Patsari homes. This would imply a maximum potential bias of 10% in estimates of particulate reductions on an aggregate basis as a result of installation of the Patsari stoves as a result of monitoring for 48 h relative to a 4-day monitoring period. Clearly, similar evaluations would need to be performed during different seasons to assess reductions in long term exposures estimates for health-based assessment, as reductions in air pollution concentrations may differ during the wet season, as a result of changes in ventilation patterns of homes and changes in fuel use. For example, although the dry season in this region of Mexico is prevalent during the majority of the year, however, and reductions seen here would represent the majority of the time, a third of participants in this community reported using the traditional fogon for heating the kitchen during the rainy season.

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